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Formation Times of Meteorites and Lunar Samples

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This article summarizes research since the last detailed reviews of meteorite ages by *Anders* [1963] and *Reynolds* [1967]. Only crystallization ages based on parent-daughter isotopic relationships resulting from the decay of naturally occurring radioactive nuclei will be discussed. The basic principles and techniques for age determinations are discussed in many of the papers cited and, along with summaries of scientific results, in several recent books [*Dalrymple and Lanphere*, 1969; *Doe* 1970; *Hamilton*, 1965; *Schaeffer and Zähringer*, 1966; *Faul*, 1966]. However, developments in the field have made some of the material in the books obsolete.

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At the end of 1966 the following results were well established:

1. An age for the earth of $4.55 \pm 0.15 \times 10^9$ years could be calculated by assuming that terrestrial oceanic lead evolved from the primordial lead found in troilite from some iron meteorites [*Patterson*, 1956],

2. Ages of about 4.6×10^9 years were obtained from $^{87}Rb - ^{87}Sr$ analyses of chondrites by assuming an initial $^{87}Sr/^{86}Sr$ ratio inferred from Ca-rich achondrites

[see, e.g., *Gast,* 1962]. (Owing to low Rb/Sr in Ca-rich achondrites, the $^{87}Sr/^{86}Sr$ ratio shows negligible evolution in 4–5 × 10^9 years.) Partial justification for this procedure can be obtained from the $^{207}Pb/^{206}Pb$ in the Nuevo Laredo achondrite, which again, under the assumption of an initial Pb composition from iron meteorites, corresponded to an age of 4.6 × 10^9 years [*Patterson,* 1956].

3. The maximum K-Ar ages of stone meteorites (mostly chondrite analyses) were 4.5–4.6 × 10^9 years, but there was a wide spread with some ages of less than 10^9 years, presumably because of diffusive ^{40}Ar loss [see, e.g., *Kirsten et al.,* 1963].

4. Silicate inclusions from the Weekeroo station iron meteorite yielded a Rb-Sr isochron corresponding to an age of 4.7 ± 0.3 × 10^9 years [*Wasserburg et al.,* 1965]; this value agreed with ages of stone meteorites and indicated that K-Ar ages of 6–10 × 10^9 years measured on the metallic phase [see, e.g., *Müller and Zähringer,* 1966] were not actual times.

5. The presence of radiogenic ^{129}Xe in chrondrites due to in situ decay of ^{129}I (17-m.y. half-life) [*Reynolds,* 1960; *Jeffery and Reynolds,* 1961] showed that the age of the chondrites could be equated with the age of the solar system. Excess $^{131\text{-}136}Xe$ was present in Ca-rich achondrites [see, e.g., *Rowe and Kuroda,* 1965], presumably owing to spontaneous fission of ^{244}Pu (80-m.y. half-life).

I shall now review the meteorite age measurements of the past 4 years, summarize the state of the art through 1970, and finally discuss age measurements on lunar samples.

The primary experimental breakthrough in the past 4 years has been for the ^{87}Rb-^{87}Sr method. Chemical extractions of Rb and Sr with subnanogram contamination levels are now possible [see, e.g., *Sanz and Wasserburg,* 1969]. This ability, coupled with high sensitivity and, particularly, high precision mass spectrometry [see, e.g., *Wasserburg et al.,* 1969*a*] make accurate age and initial ($^{87}Sr/^{86}Sr$) determinations possible on small samples with only small enrichments in $^{87}Sr/^{86}Sr$.

Chondrites

A major research problem has been obtaining Rb-Sr ages for chondrites independent of genetic assumptions relating chondrites and achondrites. Two basic approaches have been followed.

1. Accept the petrological and chemical evidence that the various chondrite subgroups are genetically related; then try to find enough variation in Rb/Sr among members of the subclass to construct a group isochron. As long as only chondrite falls are considered, this approach has yielded consistent ages (T) and initial $^{87}Sr/^{86}Sr$ (I) for hypersthene chondrites (T = 4.48 ± 14 × 10^9 years, I = 0.7008 ± 14 [*Gopalan and Wetherill,* 1968]), bronzite chondrites (4.69 ± 0.14; 0.6983 ± 24 [*Kaushal and Wetherill,* 1969]), amphoterite chondrites (4.56 ± 0.15; 0.7005 ± 2 [*Gopalan and Wetherill,* 1969]), and enstatite chondrites (4.54 ± 0.13; 0.6993 ± 10 [*Gopalan and Wetherill,* 1970]). The errors in I refer to the last significant figures. These data show no significant differences in evolution among the various chondrite subclasses. In contrast to the above results, a wide scatter was obtained for whole-rock analyses of carbonaceous chondrites [*Kaushal and Wetherill,* 1970], although an earlier, more limited, study by *Murthy and Compston* [1965] did not show this scatter clearly. Kaushal and Wetherill suggested, but could not prove, that the scatter represented terrestrial contamination. This work shows that terrestrial contamination may have to be considered when 'cosmic abundances' are calculated from trace element analyses of carbonaceous chondrites.

2. Determine an 'internal isochron,' using only data from a single meteorite, by analyzing separated minerals or different physical parts (e.g., chondrules and matrix) that have differences in Rb/Sr. This approach is preferable, although it is more difficult than the first approach. Initial attempts to determine chondrite isochrons for Peace River [*Murthy and Compston,* 1965], for Bjürbole [*Shields et al.,* 1966], and for Abee, Bruderheim, and Peace River [*Shima and Honda,* 1967] were only marginally successful in that there was considerable scatter in the results for a single meteorite. The scatter does not appear to result from extraterrestrial causes [*Sanz and Wasserburg,* 1969]. However, in the last 3 years, precise internal isochrons have been obtained from Krähenberg (T = 4.70 ± 0.02 × 10^9 years; I = 0.6989 ∓ 10 [*Kempe and Müller,* 1969]), Olivenza (4.63 ± 0.16; 0.6994 ∓ 17 [*Sanz and Wasserburg,* 1969]), Guareña (4.58 ± 0.08; 0.69995 ∓ 15 [*Wasserburg et al.,* 1969*b*]), and Indarch (4.54 ± 0.13; 0.6993 ∓ 10 [*Gopalan and Wetherill,* 1970]). In each case the errors represent the spread of the data (2σ) around a best-fit isochron. The only apparent age difference between Krähenberg and Guareña may not be significant because of the possibility of systematic interlaboratory differences in Rb spike calibrations of up to 2%. No significant I differences can be resolved.

The high-temperature minerals in many chondrites appear to have retained radiogenic ^{129}Xe within ±2 m.y. of each other [*Hohenberg et al.,* 1967*a*; *Podosek,* 1970*a*]. The oldest and youngest materials (Karoonda total rock and Chainpur chondrules) are separated in time by only 14 m.y.; however, this difference is significant.

The presence of radiogenic ^{129}Xe in nearly every chondrite (see, e.g., the compilation by *Zähringer* [1968]) probably means that none of the low whole-rock K-Ar ages for chondrites reflects the existence of young meteorites. No new conclusions have been drawn from whole-rock K-Ar data on chondrites since the discussion by *Reynolds* [1967]. Additional data are compiled by *Müller and Zähringer* [1969]. (See, also, *Funkhouser et al.* [1967], *Mazor et al.* [1970], and *Fireman et al.* [1970].) *Turner* [1969] has shown that the $^{39}Ar/^{40}Ar$ thermal release pattern for several hypersthene chondrites with whole-rock K-Ar ages of 1–2 × 10^9 years is consistent with their involvement in the

500-m.y. 'collision event' for hypersthene chondrites [see, e.g., *Heymann*, 1967].

Achondrites

Using precise ($1/10^4$) $^{87}Sr/^{86}Sr$ measurements, *Papanastassiou and Wasserburg* [1969] and *Papanastassiou* [1969] obtained a well-defined group isochron ($T = 4.47 \pm 0.24 \times 10^9$ years; $I = 0.69898 \mp 3$) for nine eucrites. Because of the low Rb/Sr ratios for these meteorites, an I value could be precisely calculated for each meteorite almost independent of the age. The tight grouping of the I values meant that, if the meteorites formed from a parent material having Rb/Sr similar to type I carbonaceous chondrites, the maximum time interval over which the formation occurred was 4 m.y. This result illustrates the point that the existence of formation time differences is more readily detected by initial $^{87}Sr/^{86}Sr$ measurements than by measurements of ages (from isochron slopes). However, time intervals can be calculated only on a model basis in contrast to actual values, which are presumably obtained from $^{129}I/^{127}I$ ratios. An approximate internal isochron for Stannern (4.1 ± 0.7; 0.6991 ∓ 2 [*Papanastassiou*, 1969]) is consistent with the group isochron. Angra dos Reis has a distinctly more primitive $I = 0.69884 \pm 4$ [*Papanastassiou*, 1969], which is equivalent to formation 14 m.y. before the eucrites if chondritic parent material is assumed.

Many achondrites have large excesses of $^{131\text{-}136}Xe$ [*Rowe and Kuroda*, 1965; *Rowe and Bogard*, 1966; *Kuroda et al.*, 1966; *Rowe*, 1967; *Hohenberg et al.*, 1967*b*; *Munk*, 1967; *Hohenberg*, 1970]. This excess heavy Xe has a well-defined isotopic spectrum [*Eberhardt and Geiss*, 1966; *Hohenberg et al.*, 1967*b*; *Wasserburg et al.* 1969*c*; *Hohenberg*, 1970] and is known to be due to fission, presumably ^{244}Pu, by its correlation with fission tracks [*Wasserburg et al.*, 1969*c*]. However, the over-all spread in the achondritic (fission $^{136}Xe)/^{238}U$ values as summarized by *Reynolds* [1968] is a factor of 10 ($\Delta T \sim 270$ m.y. for ^{244}Pu) and a factor of 5 ($\Delta T \sim 190$ m.y. for ^{244}Pu) for some eucrites that should have the same age based on initial Sr measurements. The achondritic $^{136}Xe_f/^{238}U$ is distinctly less than that for whitlockite from the St. Severin chondrite [*Wasserburg et al.*, 1969*c*] but about the same as the total St. Severin [*Podosek*, 1970*b*]. The radiogenic ^{129}Xe contents of Ca-rich achondrites are small (low ^{127}I) and uncertain, owing to the presence of comparatively large amounts of spallation ^{129}Xe. However, the Ca-poor achondrites, Shallowater [*Hohenberg*, 1967], Pena Blanca Springs, and Bishopville [*Podosek*, 1970*a*] have large ^{129}Xe excesses. All formed within 15 m.y. of most chondrites, although the formation times of Pena Blanca Springs and Bishopville are significantly younger. The extent to which achondritic $^{129}Xe/^{127}I$ and $^{136}Xe_f/^{238}U$ values are concordant is unclear [*Reynolds*, 1968].

Concordant K-Ar ages of $3.8–4.0 \times 10^9$ years from magnetic separates of Ca-rich achondrites [*Megrue*, 1966] were interpreted as showing that the low ages were not the result of Ar loss. However, Megrue did not establish that more than one K-bearing phase was being analyzed, and his conclusion must be regarded as tentative. Additional whole-rock K-Ar ages for nonchondritic stone meteorites are given by *Megrue* [1968], *Heymann et al.*, [1968], and *Ganapathy and Anders* [1969].

The well-defined internal Rb-Sr isochron for the Norton County enstatite achondrite ($T = 4.70 \pm 0.10$; $I = 0.700 \mp 2$ [*Bogard et al.*, 1967]) and more recent K-Ar age measurements [*Bogard et al.*, 1967; *Müller and Zähringer*, 1969] indicate that the 5.1×10^9-year K-Ar age reported by *Kirsten et al.* [1963] does not have time significance. A 3.7×10^9-year age from an internal Rb-Sr isochron for Bishopville [*Compston et al.*, 1965] requires confirmation because *Podosek* [1970*a*] reports an approximately chondritic $^{129}I/^{127}I$ and *Kirsten et al.* [1963] give a 4.6×10^9-year K-Ar age.

Iron Meteorites

The high 'ages' obtained by neutron activation K-Ar measurements on the metal phase [*Müller and Zähringer*, 1966; *Rancitelli et al.*, 1967] can be explained by ^{83m}Kr interference with the ^{41}Ar counting [*Kaiser and Zähringer*, 1968] and perhaps by K leaching [*Rancitelli and Fisher*, 1968]. However, reliable ages for several iron meteorites were obtained from both of silicate inclusions by both Rb-Sr [*Burnett and Wasserburg*, 1967*a*] and K-Ar [*Bogard et al.*, 1968] analyses of silicate inclusions. Rb-Sr isochrons have been determined for Weekeroo station ($T = 4.37 \pm 0.13 \times 10^9$ years; $I = 0.703 \mp 2$ [*Burnett and Wasserburg*, 1967*a*]), El Taco (4.7 ± 0.1; 0.700 ∓ 1 [*Wasserburg and Burnett*, 1969 and unpublished data]), and Colomera (4.61 ± 0.04; 0.69940 ∓ 4 [*Sanz et al.*, 1970]). Weekeroo appears to be significantly more evolved than Colomera. The Colomera I value is distinct from Guareña and the eucrites (equivalent to 35 and 39 m.y. of evolution, respectively, in a chondritic parent material). An isochron for Kodaikanal (3.8 ± 0.1; 0.71 ∓ 2 [*Burnett and Wasserburg*, 1967*b*]), confirmed by K-Ar measurements [*Bogard et al.*, 1968, 1969], provides the only evidence for the formation of a meteorite at a time significantly removed from the magic number of 4.6×10^9 years. The $^{129}I/^{127}I$ for El Taco silicate indicates that El Taco cooled sufficiently to retain ^{129}Xe only 4 m.y. after most chondrites [*Podosek*, 1970*a*]. Approximately chondritic $^{129}I/^{127}I$ has been reported for Toluca silicate [*Alexander et al.*, 1970]. The $^{244}Pu/^{238}U$ ratios estimated from excess fission tracks in diopside from El Taco [*Schirck et al.*, 1969] and Toluca [*Fleischer et al.*, 1968] are consistent with near-isochronous formation of these meteorites with chondrites.

Oversby [1970] has re-examined the problem of 'excess radiogenic' Pb in troilite from iron meteorites and has given arguments against possible origins for the anomalies other than contamination with terrestrial leads. Slightly revised values for 'primordial lead' were also proposed.

Summary—Meteorite Ages

Research in the last 4 years has justified the genetic assumptions relating various meteorite classes that were previously made in calculating meteorite ages; thus, it is now known with a very high degree of certainty that almost all meteorites, the earth, and, undoubtedly, the moon formed at the time of the isolation of the solar system around 4.6×10^9 years ago. The more precise absolute age measurements have given times between 4.5 and 4.7×10^9 years; however, the relative age measurements (initial $^{87}Sr/^{86}Sr$, $^{129}I/^{127}I$) have provided the most insight and indicate that objects of wildly different chemical composition all formed well within 100 m.y. of each other. Still more important, it appears possible to resolve events in this interval. Unfortunately, there is no overlap at present between meteorites with well-determined initial $^{87}Sr/^{86}Sr$ and $^{129}I/^{127}I$. Under the assumption that the attribution of achondritic fission Xe to ^{244}Pu can be confirmed by laboratory measurements of the fission yield spectrum, another high-resolution clock for the early solar system should be available, which has not been exploited to date. Also, new Pb isotopic investigations on meteorites are long overdue.

Age of Lunar Samples

Age measurements on Apollo 11 samples can be found in the *Science* issue (vol. 167, pp. 461–481) reporting on the First Lunar Science Conference and in papers by the same authors in volume 2 of the *Geochimica Cosmochimica,* Supplement 1, April 1970. The ages of Tranquillity base rocks ($3.6–3.7 \times 10^9$ years) appear to be best defined by high-precision Rb-Sr internal isochrons [*Albee et al.*, 1970; *Papanastassiou et al.*, 1970; *Compston et al.*, 1970] and the $^{39}Ar/^{40}Ar$ thermal release studies [*Turner,* 1970*a*]. All lower-precision Rb-Sr studies now appear to be in essential agreement with these ages [*Gopalan et al.*, 1970; *Gast et al.*, 1970; *Hurley and Pinson,* 1970]. Only the nominally high-precision Rb-Sr study by *Murthy et al.* [1970] gives ages that are in serious disagreement with 3.7×10^9 years. Very primitive initial $^{87}Sr/^{86}Sr$ values were obtained that indicate that the moon as a whole probably did not form significantly later than 4.6×10^9 years [*Papanastassiou et al.*, 1970]. Whole-rock K-Ar measurements have been of limited value for either Apollo 11 [*Lunar Sample Preliminary Examination Team,* 1969; *Albee et al.*, 1970; *Eberhardt et al.*, 1970; *Marti et al.*, 1970; *Funkhauser et al.*, 1970] or Apollo 12 rocks [*Lunar Sample Preliminary Examination Team,* 1970; *Schaeffer et al.*, 1970], owing to loss of ^{40}Ar [*Albee et al.*, 1970; *Eberhardt et al.*, 1970]. The interpretation of the Pb isotopic data is more difficult because of the uncertainties in the initial lead compositions. The high U and Th enrichments and the depletion of chalcophile elements in lunar materials imply that the initial leads may have been very radiogenic. However, *Tatsumoto* [1970*a*] and *Silver* [1970] show that there is no single initial lead isotopic composition that can yield concordant U-Pb and Th-Pb ages of $3.6–3.8 \times 10^9$ years for all rocks. A variety of initial leads must be assumed such that the more U-rich rocks require more radiogenic initial leads. *Silver* [1970] argues that this assumption is unreasonable and that, because approximately concordant U-Pb ages are obtained when either primordial or terrestrial initial lead compositions are assumed, the $^{207}Pb/^{206}Pb$ ages so obtained ($4.0–4.1 \times 10^9$ years) may represent a primary time of crystallization, whereas the Rb-Sr isochrons and $^{39}Ar/^{40}Ar$ ages date a secondary episode. However, as suggested by *Tatsumoto* [1970*a*], selective contamination with U from the country rock intruded by the Tranquillity base lavas could produce the required correlation of U and initial ^{207}Pb and ^{206}Pb contents. In this context, it is interesting to note that the 'high-Rb rocks' [*Compston et al.*, 1970] have distinctly higher initial $^{87}Sr/^{86}Sr$ (about 0.6994) than the low-Rb rocks (0.6991) [*Albee et al.*, 1970; *Papanastassiou et al.*, 1970].

Rb-Sr internal isochrons for Apollo 12 basalts give ages of $3.2–3.3 \times 10^9$ years [*Papanastassiou and Wasserburg,* 1970], which are considerably higher than were expected on the basis of relative crater densities in Oceanus Procellarum and Mare Tranquillitatis.

In an issue of *Earth and Planetary Science Letters* (vol. 9, pp. 93–211, 1970) devoted to rock 12013, *Turner* [1970*b*] shows that fragments of both the light and dark portions give $^{40}Ar/^{39}Ar$ ages of 3.9×10^9 years. Rb-Sr isochrons for mineral separates from two small fragments give identical ages of 4.0×10^9 years, however, with two distinct initial $^{87}Sr/^{86}Sr$ values (0.7050 and 0.7085) indicating that the final local Sr isotopic re-equilibration occurred at that time [*Lunatic Asylum,* 1970]. However, 'total fragment' analyses were distributed approximately along a 4.5×10^9-year isochron indicating that the parent material(s) of 12013 had behaved approximately as a closed system with respect to Rb and Sr in the period from 4.6 to 4.0×10^9 years [see, also, *Schnetzler et al.*, 1970]. Discordant U-Pb and Th-Pb ages are observed for 12013 regardless of the assumed initial Pb compositions; however, approximately concordant U-Pb ages of $3.7–3.9 \times 10^9$ years can be obtained with an appropriately chosen initial lead composition [*Tatsumoto,* 1970*b*].

The Tranquillity base soil gives a model Rb-Sr age of 4.6×10^9 years [*Papanastassiou et al.*, 1970] and concordant Pb-U-Th ages of about 4.65×10^9 years [*Tatsumoto,* 1970*a*; *Silver,* 1970; *Gopalan et al.*, 1970]. Apollo 12 soil 12070 gives a slightly lower model Rb-Sr age of 4.4×10^9 years [*Papanastassiou and Wasserburg,* 1970]. Because the soil is a mixture including fragments from young rocks, these values are not ages in the usual sense; however, these striking results provide the strongest evidence that the lunar soil contains a 'magic' component or components that, either with or without significant contributions from local rocks, probably have preserved the isotopic ratios dating a major fractionation event early in the history of the moon. By volatilization and leaching experiments *Silver* [1970] has shown that a loosely bound almost U-free Pb component is present in Tranquillity base soil which has a very high $^{207}Pb/^{206}Pb$. This component is presumably the ancient Pb associated with the magic component, and its presence can account for a high $^{207}Pb/^{206}Pb$ age. The concordant U-Pb and Th-Pb ages are more difficult to understand.

In comparison, the isotopic relations in lunar samples appear to be somewhat more complex than those in meteorites. On the other hand, this complexity promises to be rich in information about the evolution of the moon. For example, it is conceivable that initial lead measurements could play the same role for lunar samples as initial Sr measurements have played for meteorites, only with much greater sensitivity for evolutionary differences. Moreover, the simple fact that lunar samples came from a known solar system object of planetary size cannot be overemphasized. Determination of the evolution of a small planet from isotopic studies on lunar rocks, coupled with related petrological, chemical, and geophysical studies, may be a less formidable task (given adequate sampling) than working out the evolution of the earth from measurements on terrestrial rocks. It is questionable, however, whether a sufficient sampling can be obtained in the few remaining Apollo missions to allow the proverbial 'big picture' to be assembled. An on-going program of lunar exploration is required.

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